SPIN AND 3D STRUCTURE

Alessandro Bacchetta and Alexei Prokudin
Not only a world-expert in spin and 3D structure, but also post-doc in Torino from 2001 to 2009
RELEVANT LITERATURE
QCD and the Structure of Nucleons and Nuclei

Understanding the structure of hadrons in terms of QCD’s quarks and gluons is one of the central goals of modern nuclear physics.

QCD – the Last Frontier of the Standard Model

A relativistic quantum theory of strong interacting quarks and gluons.

BUT, we do not see any quarks and gluons in isolation!

"Unprecedented intellectual challenge: How to test a theory without seeing the players?"

Understanding QCD fully is still beyond the reach of the best minds we have!
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RECOMMENDATION I

... 

- With the imminent completion of the CEBAF 12-GeV Upgrade, its forefront program of using electrons to unfold the quark and gluon structure of hadrons and nuclei and to probe the Standard Model must be realized.

... 

- The upgraded RHIC facility provides unique capabilities that must be utilized to explore the properties and phases of quark and gluon matter in the high temperatures of the early universe and to explore the spin structure of the proton.
QCD and the Structure of Nucleons and Nuclei

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RECOMMENDATION III

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new quantum chromodynamics (QCD) frontier.

…
Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?
The field of “spin and 3D structure” is prominently included in the strategic plans of the US. We hope that the EU will give an equally strategic support!
Wigner distributions (Fourier transform of GTMDs = Generalized Transverse Momentum Distributions)

• There are eight TMD distributions in leading twist
• TMD distributions provide a more detailed picture of the many body parton structure of the hadron
• Interplay with the transverse momentum

see, e.g., C. Lorcé, B. Pasquini, M. Vanderhaeghen, JHEP 1105 (11)
SPIN
HELICITY PARTON DISTRIBUTION FUNCTIONS

longitudinally polarized target

longitudinally polarized quark

Sato et al., arXiv:1601.07782

arXiv:1711.07916
Remarkable agreement between extracted moments of helicity distributions and lattice QCD calculations
PARTON’S CONTRIBUTIONS TO ANGULAR MOMENTUM

We are constantly improving the knowledge of the contributions to the spin of the proton
Transversity Parton Distribution Function

Anselmino et al., arXiv:1510.05389

Radici, Bacchetta, arXiv:1802.05212

Martin, Bradamante, Barone, arXiv:1412.5946

Lin et al., arXiv:1710.09858

Transversely polarized target

Transversely polarized quark

\[ Q^2 = 2.4 \text{ GeV}^2 \]
At the moment, there is a clear tension between extractions and lattice calculations.

Tensor charge

\[ \delta q \equiv g_T^q = \int_0^1 dx \left[ h_1^q(x, Q^2) - h_1^q(x, Q^2) \right] \]

- Alexandrou et al., arXiv:1703.08788
- Gupta et al., arXiv:1806.09006
- Anselmino et al., arXiv:1303.3822
- Kang et al., arXiv:1505.05589
- Lin et al., arXiv:1710.09858
- Radici et al., arXiv:1802.05212
Tensor couplings, not present in the SM Lagrangian, could be the footprints of new physics at higher scales.

\[ \varepsilon_T \, g_T \approx \frac{M_W^2}{M_{BSM}^2} \]

Current precision of 0.1% \implies [3-5] TeV bound for BSM scale

Knowledge of tensor charge is crucial.
Consider polarized hadron - hadron collisions

Count pions going to the right or to the left with respect to the spin direction

\[ A_N \equiv \frac{\sigma(\vec{s}_P) - \sigma(-\vec{s}_P)}{\sigma(\vec{s}_P) + \sigma(-\vec{s}_P)} \]
CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

QCD had a very simple prediction

\[ A_N \propto \alpha_s \frac{m_q}{P_T} \rightarrow 0 \]

Kane, Pumplin, Repko (1978)

Experiment proved this prediction wrong

Fermilab experiment E704 (1991)

\[ \sqrt{s} \approx 19 \text{ (GeV)} \]
CHALLENGE OF QCD: UNDERSTANDING SPIN ASYMMETRIES

Asymmetry survives with growing collision energy

RHIC: STAR, BRAHMS, PHENIX

“The RHIC SPIN Program: Achievements and Future Opportunities”, Aschenauer et al (15)
FAILURE OF QCD?
BETTER UNDERSTANDING OF QCD!
Multi-parton correlations (twist-3 functions) contribute to the cross section and are dominant for asymmetries.

Collinear objects related to TMDs via Operator Product Expansion.
Explanation using fit of twist-3 fragmentation functions

Prediction of $A_N$ at STAR using only SIDIS and $e^+e^-$ data information only
Spin physics is making a lot of progress

Spin physics can have an impact also on BSM searches
3D STRUCTURE
The Y term guarantees that the calculation at high $P_{hT}$ agrees with perturbative calculation done with collinear factorization.

$$F_{UU,T}(x, z, P_{hT}^2, Q^2) = x \sum_a H_{UU,T}^a(Q^2; \mu^2) \int \frac{db_{\perp}^2}{4\pi} J_0(|\mathbf{b}_T| |\mathbf{P}_{h\perp}|) f_1^a(x, z^2 b_{\perp}^2; \mu^2) D_1^{\perp}(z, b_{\perp}^2; \mu^2)$$

$$+ Y_{UU,T}(Q^2, P_{hT}^2) + \mathcal{O}(M^2/Q^2)$$

The Y term guarantees that the calculation at high $P_{hT}$ agrees with perturbative calculation done with collinear factorization.

$$\tilde{f}_1^a(x, b_T; \mu^2) = \sum_i \left( \tilde{C}_{a/i} \otimes f_1^i \right)(x, b_*; \mu_b) e^{\tilde{S}(b_*; \mu_b, \mu)} e^{g_K(b_T) \ln \frac{\mu}{\mu_0}} \hat{f}_{NP}^a(x, b_T)$$

**W term**

**collinear PDF**

**pQCD**

**nonperturbative part of evolution**

**nonperturbative part of TMD**

---

see, e.g., Rogers, Aybat, PRD 83 (11), Collins, “Foundations of Perturbative QCD” (11)

other possible schemes, e.g.,

Laenen, Sterman, Vogelsang, PRL 84 (00)
Bozzi, Catani, De Florian, Grazzini, NPB737 (06)
Echevarria, Idilbi, Schaefer, Scimemi, EPJ C73 (13)
## TMD Fits of Unpolarized Data

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<th>Framework</th>
<th>W+Y</th>
<th>HERMES</th>
<th>COMPASS</th>
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<td>✔</td>
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<td>✔</td>
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<td>×</td>
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x–Q² COVERAGE

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

Bertone, Scimemi, Vladimirov, arXiv:1902.08474
3D DISTRIBUTIONS EXTRACTED FROM DATA

Bacchetta, Delcarro, Pisano, Radici, Signori, arXiv:1703.10157

Bertone, Scimemi, Vladimirov, arXiv:1902.08474
PROBLEMS WITH HIGH TRANSVERSE MOMENTUM


COMPASS 17 $h^+$
data/theory(LO) vs. $q_T$ (GeV)
PDF : CJ15 FF : DSS07

At high $q_T$, the collinear formalism should be valid, but large discrepancies are observed
PROBLEMS WITH HIGH TRANSVERSE MOMENTUM

The discrepancies could be largely resolved by sharply modifying the gluon collinear fragmentation function
However, large discrepancies are found also in low-energy DY scattering data.
First direct measurement of TMD effects in fragmentation functions
Makes use of thrust axis: the formalism should take it into account
There is room for flavour dependence, but we don’t control it well
All analyses assume that TMDs are not flavour dependent. What happens if they are?

\[
m_W = 80370 \pm 7 \text{ (stat.)} \pm 11 \text{ (exp. syst.)} \pm 14 \text{ (mod. syst.)} \text{ MeV} \\
= 80370 \pm 19 \text{ MeV},
\]

\[
m_{W^+} - m_{W^-} = -29 \pm 28 \text{ MeV}.
\]
### IMPACT ON W MASS DETERMINATION

Try some judicious choices of flavour dependent widths and check

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<td>0.29</td>
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- narrow, medium, large
- narrow, large, narrow
- large, narrow, large
- large, medium, narrow
- medium, narrow, large

<table>
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<th>Set</th>
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<td>-4</td>
</tr>
<tr>
<td>5</td>
<td>-1</td>
<td>-3</td>
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</table>

Not taking into account the flavour dependence of TMDs can lead to errors in the determination of the W mass.
Recent ATLAS measurement used Pythia8 to 'fit' the Z pT distribution and extrapolate to W pT. Resulting tune (AZ) reproduces the Z pT at spectrum 1-2% level. What about using resummed calculations to obtain the W/Z ratio? Higher order (NNLL, N3LO) calculations should be a good idea. W pT modeling and uncertainties is of great interest to experimentalists working on the W mass measurement. Benchmarking of resummed calculations!

Precision measurements require well-tuned MC tools. Important effects at low pT come from nonperturbative TMD components. Efforts are going also into including spin in PYTHIA.
An Assessment of U.S.-Based Electron-Ion Collider Science

Figure 2.7: Transverse momentum profile of anti-up ($\bar{u}$–$u$) and anti-down ($\bar{d}$–$d$) quarks in a proton. The figure shows three slices, ranging from the valence quark region at large Bjorken $x$ to the sea quark regime at low $x$. The color range is from zero (dark blue) to largest positive values (deep red). The transverse momentum is given in units of GeV. The visible distortion of the $\bar{d}$–anti-down quark profile at large $x$ is a signature of the correlation of a large quark orbital angular momentum with the spin of the proton. The spin direction of the proton is indicated by the red arrow. Extrapolations to the smallest $x$, using a simple analytic function, are given for illustration. SOURCE: Z.-E. Meziani and A. Prokudin.
SIVERS FUNCTION SIGN CHANGE

Sivers function SIDIS = Sivers function Drell–Yan

Collins, PLB 536 (02)

\[ \pi^- P \rightarrow \ell^+ \ell^- X \]

\[ A_N \]

\[ 0.5 < P_T^W < 10 \text{ GeV/c} \]

\[ y^W \]

\[ A_T \]

\[ x_F \]

\[ \chi^2/\text{d.o.f.} = 19.6/6 \]

3.4% beam pol. uncertainty not shown

STAR p-p 500 GeV (L = 25 pb⁻¹)

KQ (no “sign change”)

Global \[ \chi^2/\text{d.o.f.} = 19.6/6 \]

prediction with TMD evolution equations

STAR Collab. arXiv:1511.06003


SIVERS FUNCTION SIGN CHANGE

Anselmino, Boglione, D’Alesio, Murgia, Prokudin JHEP 1704 (2017) 046
We observe the following: First, the three lattice ensembles with different pion masses \((m_\pi = 518 \text{ MeV} \text{ versus } m_\pi = 300 \text{ MeV})\) and different discretization schemes at different values of the lattice spacing give consistent results. Second, as \(|b_T|\) and/or \(\zeta\) are increased, the lattice results tend toward the phenomenologically extracted value. Third, the observed behavior is similar to that seen in the study using pions in Ref. \([10]\). Thus, taking the trend in our data between 0.2 < \(\zeta\) < 0.41 at face value, it is reasonable to expect future lattice estimates at \(\zeta \approx 0.8\) to agree with the phenomenological value.

VI. CONCLUSION

We present Lattice QCD results for the time-reversal odd generalized Sivers and Boer-Mulders transverse momentum shifts applicable to SIDIS and DY experiments; and for the \(T\)-even generalized transversity, related to the tensor charge, and the generalized \(g_1\) worm-gear shift. The lattice calculations were performed on two different \(n_f = 2 + 1\) flavor ensembles: a DWF ensemble with lattice spacing \(a = 0.084 \text{ fm}\) and pion mass 297 MeV, and a clover ensemble with \(a = 0.114 \text{ fm}\) and pion mass 317 MeV. The high statistics analysis of the clover ensemble yields estimates with \(O(10\%)\) uncertainty for all four quantities over the range \(|b_T| < 0.8 \text{ fm}\) and \(\zeta < 0.3\). Estimates from the DWF ensemble have appreciably higher statistical errors owing to the more limited statistics, but are expected to have smaller systematic uncertainties. Our results for TMD observables on two ensembles with comparable pion masses, but with very different discretization of the Dirac action provide an opportunity for an empirical test of the presence of finite lattice spacing effects and the cancellation of renormalization factors in.

Yoon et al., arXiv:1706.03406

Pioneering lattice studies are in agreement with phenomenology.
Fast progress in TMD determinations is taking place, but still many open questions.

As TMDs are known better and better, they can be used to improve high-energy precision measurements.
Compton Form Factors are extracted from data

They are fitted with some ansatz and the slope at $t=0$ for each value of $\xi$ is extracted

$$H_{Im}(\xi, t) = A(\xi)e^{B(\xi)t}$$

Dupré, Guidal, Niccolai, Vanderhaeghen, arXiv:1704.07330
IMPACT PARAMETER DISTRIBUTIONS

Dupré, Guidal, Niccolai, Vanderhaeghen, arXiv:1704.07330

COMPASS coll., arXiv:1802.02739
The study of the multidimensional structure of the proton can in principle allow us to access the proton energy-momentum tensor

**Neutron stars equation of state**

![Graph showing pressure distribution in the proton]


The knowledge of pressure in hadronic matter can in principle allow us to make predictions on the behaviour of neutron stars Tantalizing results. Need more solid underpinning.
WIGNER DISTRIBUTIONS

Exclusive dijet production

Hatta, Xiao, Yuan, arXiv:1601.01585
Hatta, Nakagawa, Xiao, Yuan, Zhao, arXiv:1612.02445
Ji, Yuan, Zhao, arXiv:1612.02438

Exclusive double Drell-Yan

Bhattacharya, Metz, Zhou, arXiv:1702.04387
Our knowledge of GPDs keeps increasing

The study of the structure of the proton can have an impact even on astrophysics
THE FUTURE
“NEW” DATA FROM HERMES!

Even if the experiments was closed 10 years ago, they are still producing results

HERMES Collab., arXiv:1903.08544

Multidimesional binning
NEW DATA FROM COMPASS

COMPASS is in “full swing” mode. The collaboration is presenting 8 contributions to the spin Working Group.

COMPASS Collab., arXiv:1709.07374
FIRST JLAB PRELIMINARY DATA

Figure 3: Virtual-photon asymmetry amplitudes for positively and negatively charged pions, as measured by HERMES on a deuterium target (blue circles), and unidentified hadrons, as measured by COMPASS on a 6LiD target (grey squares), as a function of $x_B$, $z$, and $P_h^2$. The open data points from the HERMES measurement represent the region for which $z > 0$, and are not included in the representations as a function of $x_B$ and $P_h^2$, while the COMPASS measurement covers the range up to $z = 0.85$ for all projections. The error bars represent the statistical uncertainties, while the error bands represent systematic uncertainties. In addition, there is a systematic uncertainty for the HERMES results originating from the measurement of the beam polarization, corresponding to a scale factor of 3%.

Only 2% of approved data taking!
THE ELECTRON-ION COLLIDER PROJECT

BNL concept

- High luminosity: \((10^{34} \text{ cm}^{-2} \text{ s}^{-1})\)
- Variable CM energy: 20-100 GeV
- Highly polarized beams
- Protons and other nuclei

JLab concept
LHCb FIXED TARGET, INCLUDING POLARISATION

https://indico.cern.ch/event/755856/

Polarised target
VELO and SMOG2

L+C spin

For the future HL-LHC-25ns, the maximum Luminosity would be up to $8.3 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$.
ALICE FIXED TARGET

Possible fixed-target positioning

https://indico.cern.ch/event/755856/
There are eight TMD distributions in leading twist. TMD distributions provide a more detailed picture of the many-body parton structure of the hadron. Interplay with the transverse momentum $b_T$. 

\[
q(x, b) = f_1(x, b) + i \mu \nu T b_\mu f \rho
\]